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Title:	Double Beta Decay
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Intended for:	Review of underground facility and double-beta decay and dark matter experiments in Korea. I am a reviewer because of my expertise in double beta decay. I will present background material at a short symposium covering material for the review.



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Double Beta Decay

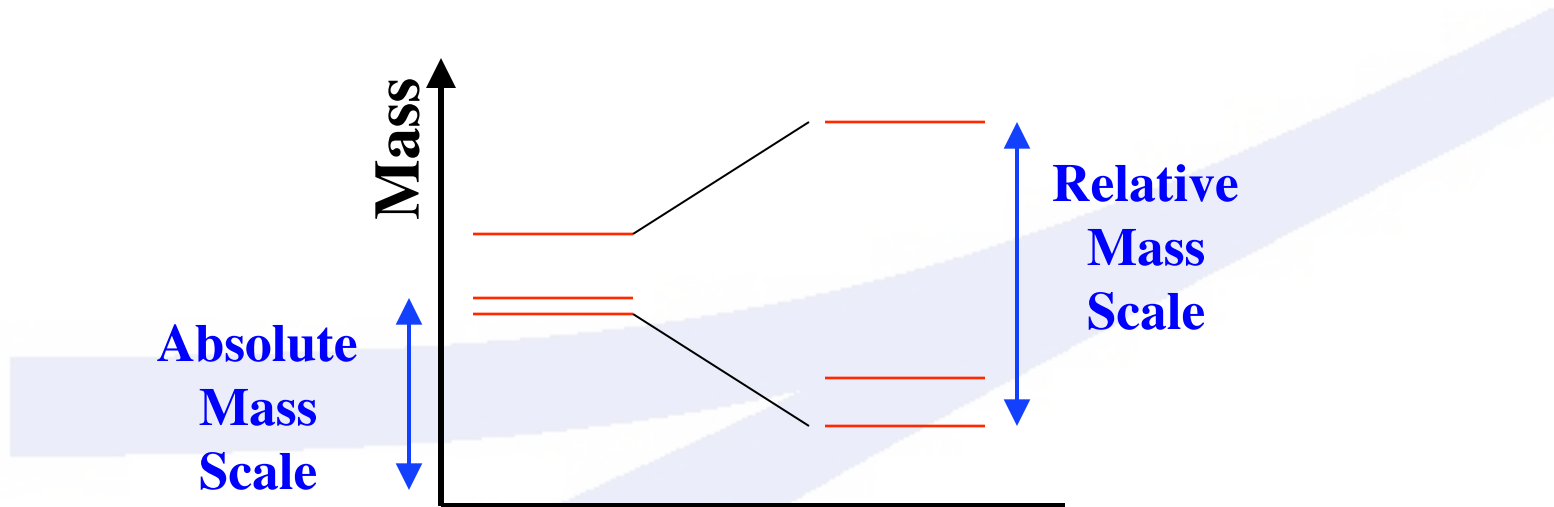
- **Neutrinos**
- **Science of $\beta\beta$**
- **MAJORANA DEMONSTRATOR**

Why Neutrinos?



- ✓ **properties are critical input to many physics questions**
- **Particle/Nuclear Physics**
 - Fundamental questions about standard model
 - Fundamental issues regarding interactions
- **Cosmology**
 - Large scale structure
 - Leptogenesis and matter-antimatter asymmetry
- **Astrophysics**
 - Supernova explosions
 - Solar burning

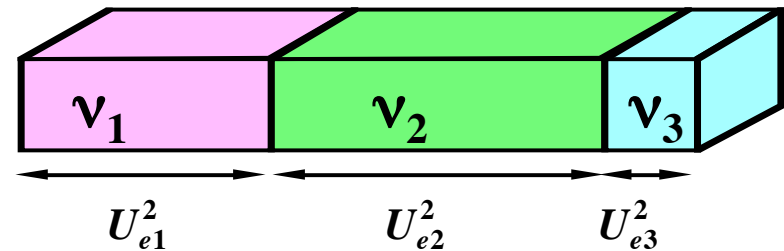
Neutrinos: What do we want to know?



Dirac or Majorana

$$\begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \\ \bar{\nu}_{\downarrow} \\ \bar{\nu}_{\uparrow} \end{pmatrix} \text{ or } \begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \end{pmatrix}$$

ν_e



Mixing



Neutrino Masses: What do we know?

- The results of oscillation experiments **indicate ν do have mass!**, set the relative mass scale, and a minimum for the absolute scale.
- β decay experiments set a maximum for the absolute mass scale.

$$50 \text{ meV} < m_\nu < 2200 \text{ meV}$$

We also know ν mix.



The weak interaction produces ν_e, ν_μ, ν_τ .

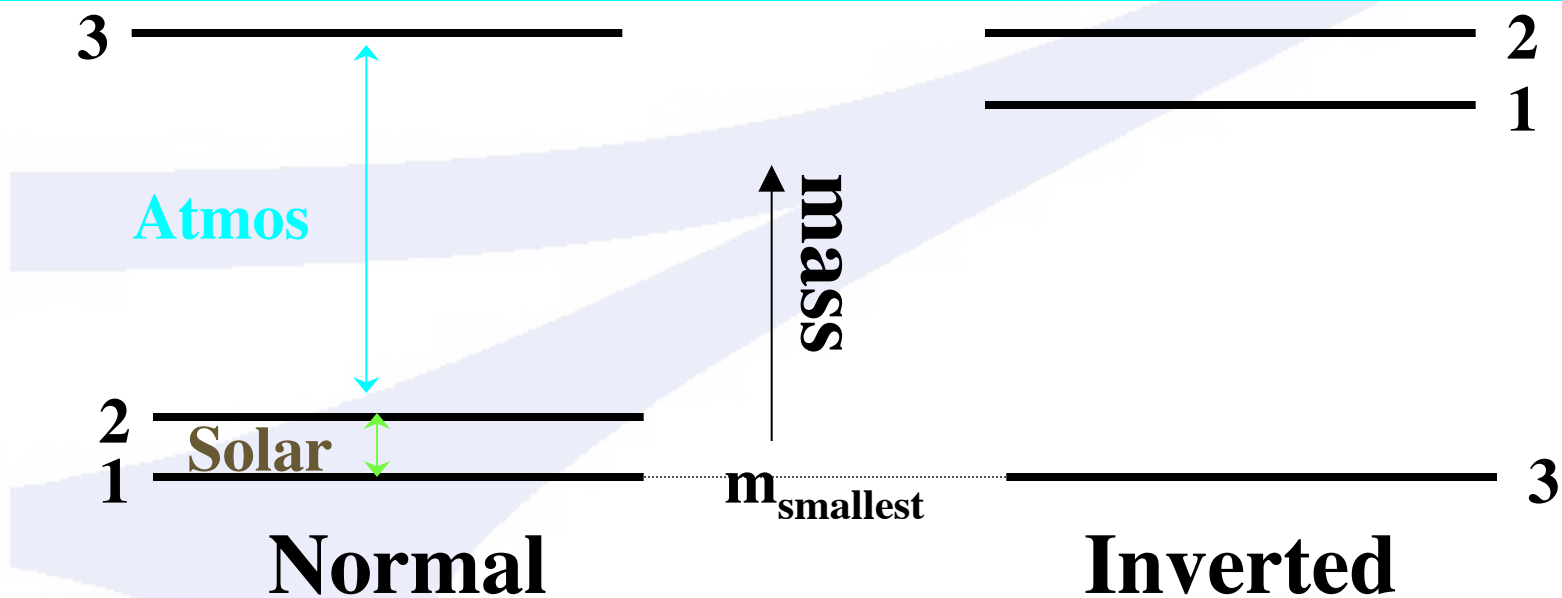
These are not pure mass states but a linear combination of mass states.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillation experiments indicate that ν mix and constrain $U_{\alpha i}$.



The Neutrino Mass Spectrum: Oscillations and Hierarchy Possibilities

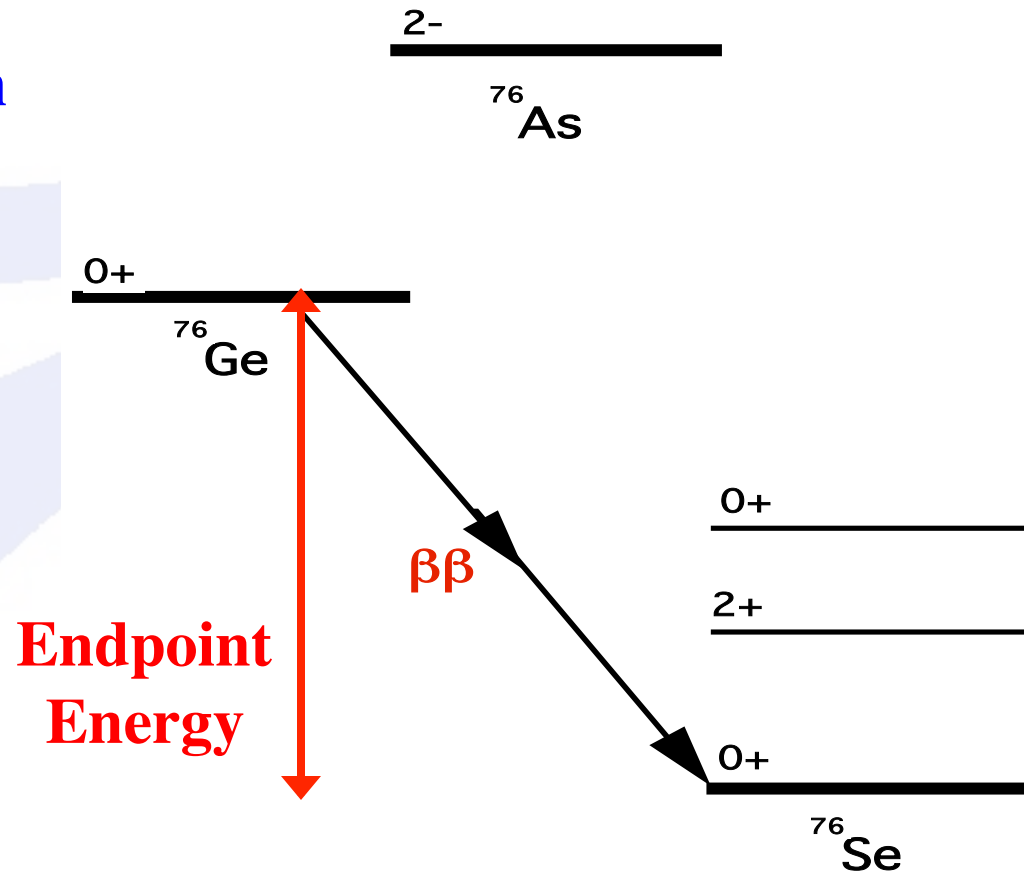


ν_e is composed of a large fraction of ν_1 .

Example $\beta\beta$ Decay Scheme



In many even-even nuclei, β decay is energetically forbidden. This leaves $\beta\beta$ as the allowed decay mode.





What is $\beta\beta$?

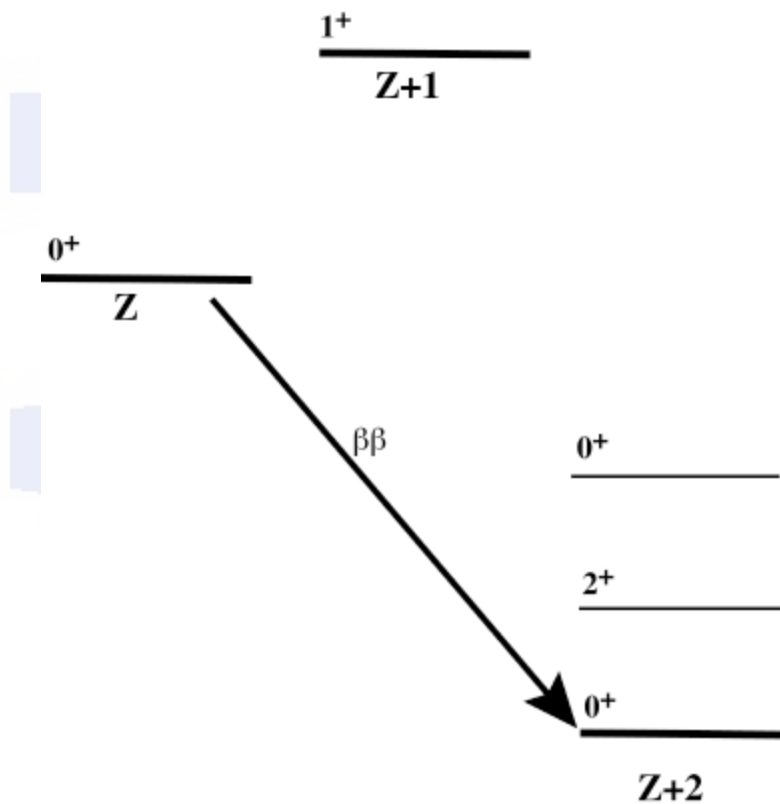


Fig. from arXiv:0708.1033

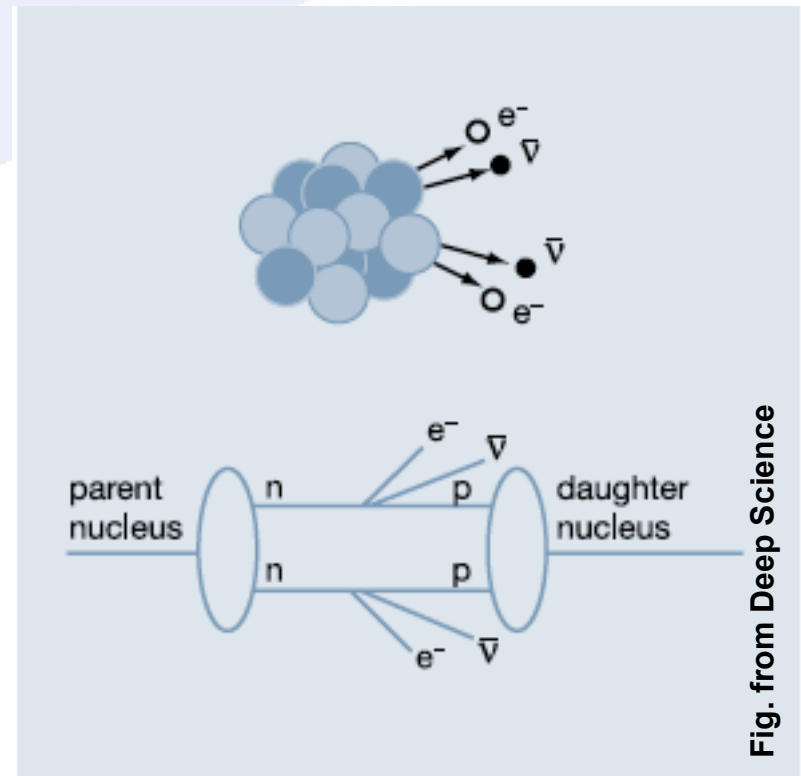


Fig. from Deep Science



What is $\beta\beta$?

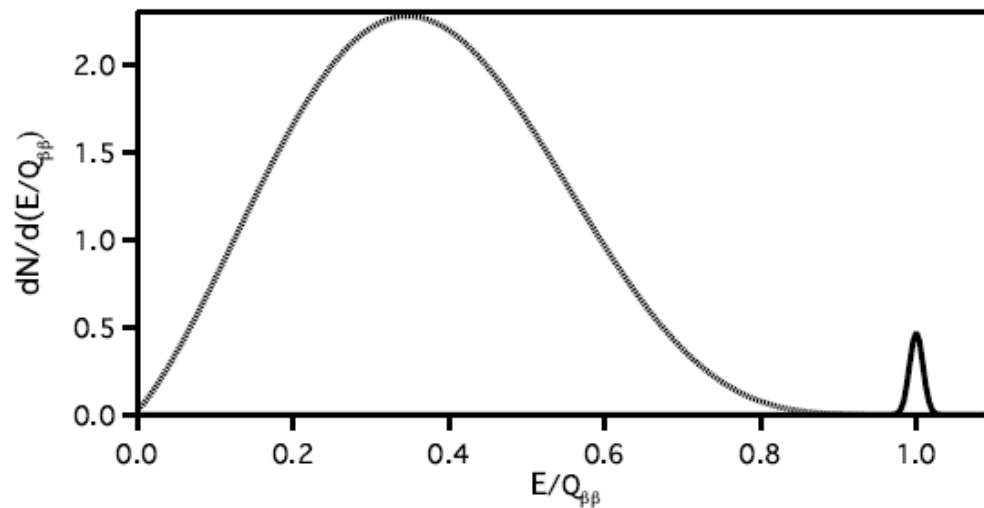


Fig. from arXiv:0708.1033

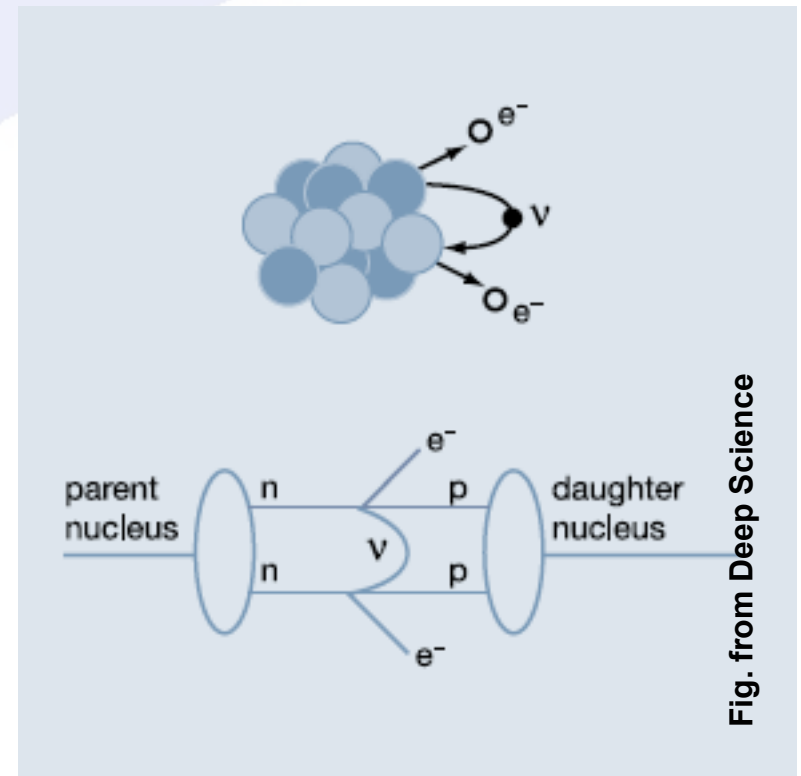


Fig. from Deep Science



$\beta\beta$ Decay Rates

$$\Gamma_{2\nu} = G_{2\nu} |M_{2\nu}|^2$$

$$\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 m_\nu^2$$

G are calculable phase space factors.

$$G_{0\nu} \sim Q^5$$

|M| are nuclear physics matrix elements.

Hard to calculate.

m_ν is where the interesting physics lies.



What about mixing, m_ν & $\beta\beta(0\nu)$?

No mixing: $\langle m_{\beta\beta} \rangle = m_{\nu_e} = m_1$

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^3 |U_{ei}|^2 m_i \varepsilon_i \quad \text{virtual } \nu \text{ exchange}$$

$\varepsilon = \pm 1$, CP cons.

Compare to β decay result:

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^3 |U_{ei}|^2 m_i^2}$$

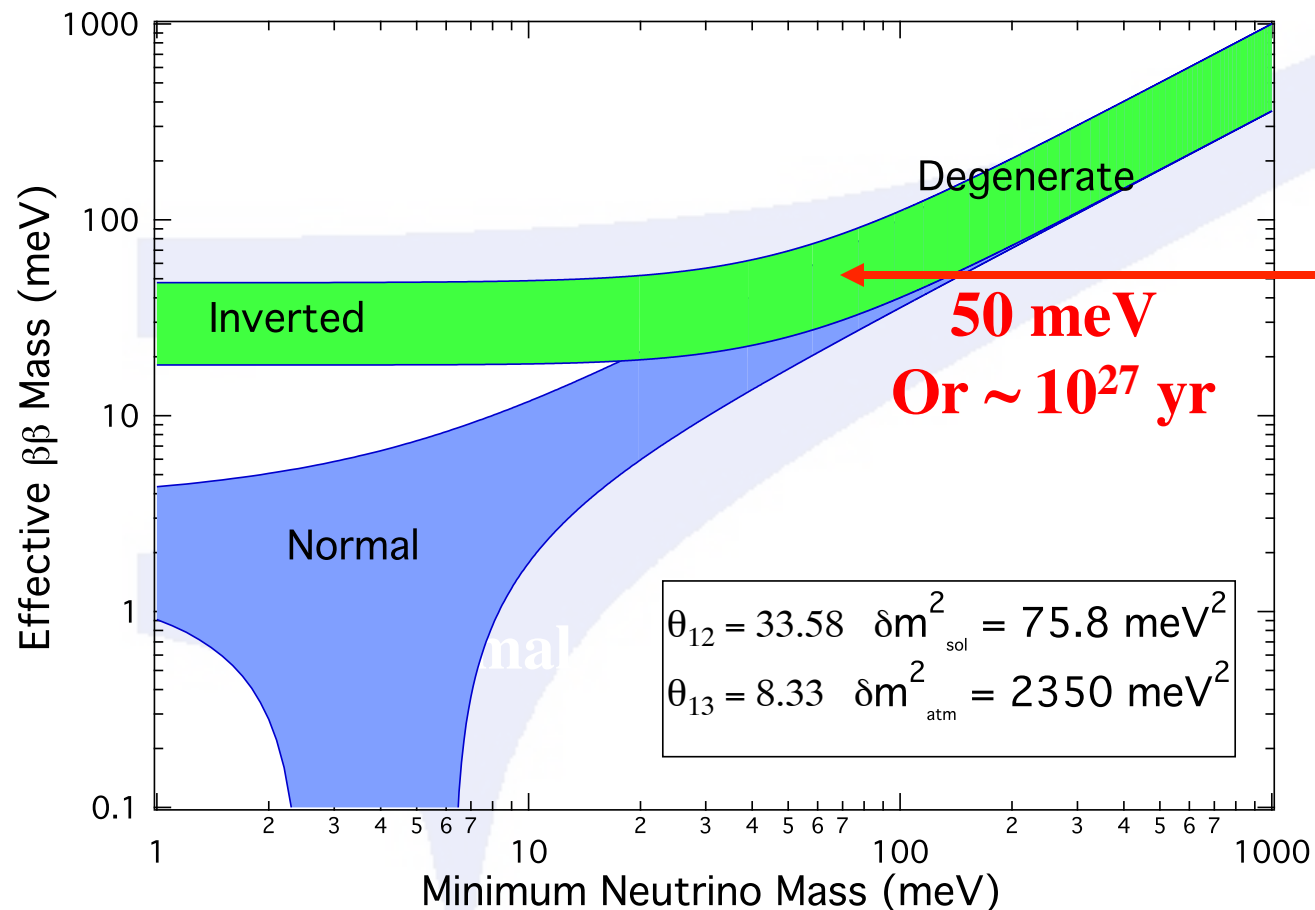
**real ν
emission**

Compare to cosmology:

$$\Sigma = \sum m_i$$

$\beta\beta$ Sensitivity

(mixing parameters from arXiv:1106.6028)



Even a null result will constrain the possible mass spectrum possibilities!

A $m_{\beta\beta}$ limit of ~ 20 meV would exclude Majorana neutrinos in an inverted hierarchy.



$\beta\beta$ and the neutrino

- $\beta\beta(0\nu)$ decay rate proportional to neutrino mass
 - Most sensitive technique (if Majorana particle)
- Decay can only occur if Lepton number conservation is violated
 - Leptogenesis?
- Decay can only occur if neutrinos are massive Majorana particles
 - Critical for understanding incorporation of mass into standard model
 - $\beta\beta$ is only practical experimental technique to answer this question
- Fundamental nuclear/particle physics process



There are a lot of them!

March 18, 2013



How to choose a $\beta\beta$ isotope?

- **Detector technology exists**
- **High isotopic abundance or an enriched source exists.**
- **High energy = fast rate, above background**



$\beta\beta$ Candidates

Abundance > 5%, Trans. Energy > 2 MeV

Hydrogen 1 H 1.00794																		Helium 2 He 4.00260																					
Lithium 3 Li 6.941				Beryllium 4 Be 9.0122														Neon 10 Ne 20.1797																					
Sodium 11 Na 22.98976928				Magnesium 12 Mg 24.304														Argon 18 Ar 39.948																					
Potassium 19 K 39.0983				Calcium 20 Ca 40.078				Scandium 21 Sc 44.955912		Titanium 22 Ti 47.88		Vanadium 23 V 50.9415		Chromium 24 Cr 51.9961		Manganese 25 Mn 54.938045		Iron 26 Fe 55.845		Cobalt 27 Co 58.933195		Nickel 28 Ni 58.6934		Copper 29 Cu 63.546		Zinc 30 Zn 65.38		Gallium 31 Ga 69.723		Germanium 32 Ge 72.630		Arsenic 33 As 74.9216		Selenium 34 Se 78.96		Bromine 35 Br 79.904		Krypton 36 Kr 83.80	
Rubidium 37 Rb 85.4678				Strontium 38 Sr 87.62				Yttrium 39 Y 88.90584		Zirconium 40 Zr 91.224		Niobium 41 Nb 92.90638		Molybdenum 42 Mo 95.94		Technetium 43 Tc [98]		Ruthenium 44 Ru 101.07		Rhodium 45 Rh 102.9055		Palladium 46 Pd 106.42		Silver 47 Ag 107.8682		Cadmium 48 Cd 112.411		Indium 49 In 114.818		Tin 50 Sn 118.710		Antimony 51 Sb 121.757		Tellurium 52 Te 127.60		Iodine 53 I 126.905		Xenon 54 Xe 131.29	
Cesium 55 Cs 132.90545196				Barium 56 Ba 137.327				Lanthanum 57 La 138.90471		Hafnium 72 Hf 178.49		Tantalum 73 Ta 180.94788		Tungsten 74 W 183.84		Rhenium 75 Re 186.207		Osmium 76 Os 190.23		Iridium 77 Ir 192.222		Platinum 78 Pt 195.084		Gold 79 Au 196.966569		Mercury 80 Hg 200.59		Thallium 81 Tl 204.38		Lead 82 Pb 207.2		Bismuth 83 Bi 208.980399		Polonium 84 Po [209]		Astatine 85 At [210]		Radon 86 Rn [222]	
Francium 87 Fr [223]				Radium 88 Ra [226]				Actinium 89 Ac [227]		Thorium 90 Th 232.0377		Protactinium 91 Pa 231.03688		Uranium 92 U 238.02891		Neptunium 93 Np [237]		Plutonium 94 Pu [244]		Americium 95 Am [243]		Curium 96 Cm [247]		Berkelium 97 Bk [247]		Californium 98 Cf [251]		Einsteinium 99 Es [252]		Fermium 100 Fm [257]		Mendelevium 101 Md [258]		Nobelium 102 No [259]					

Lanthanum 57 La 138.90471		Cerium 58 Ce 140.12		Praseodymium 59 Pr 140.90765		Neodymium 60 Nd 144.242		Promethium 61 Pm [144]		Samarium 62 Sm 150.91961		Europium 63 Eu 151.964		Gadolinium 64 Gd 157.25		Terbium 65 Tb 158.92534		Dysprosium 66 Dy 162.5001		Holmium 67 Ho 164.93032		Erbium 68 Er 167.259		Thulium 69 Tm 168.93274		Ytterbium 70 Yb 173.044	
Actinium 89 Ac [227]		Thorium 90 Th 232.0377		Protactinium 91 Pa 231.03688		Uranium 92 U 238.02891		Neptunium 93 Np [237]		Plutonium 94 Pu [244]		Americium 95 Am [243]		Curium 96 Cm [247]		Berkelium 97 Bk [247]		Californium 98 Cf [251]		Einsteinium 99 Es [252]		Fermium 100 Fm [257]		Mendelevium 101 Md [258]		Nobelium 102 No [259]	

 Frequently studied isotope.



$\beta\beta$ History

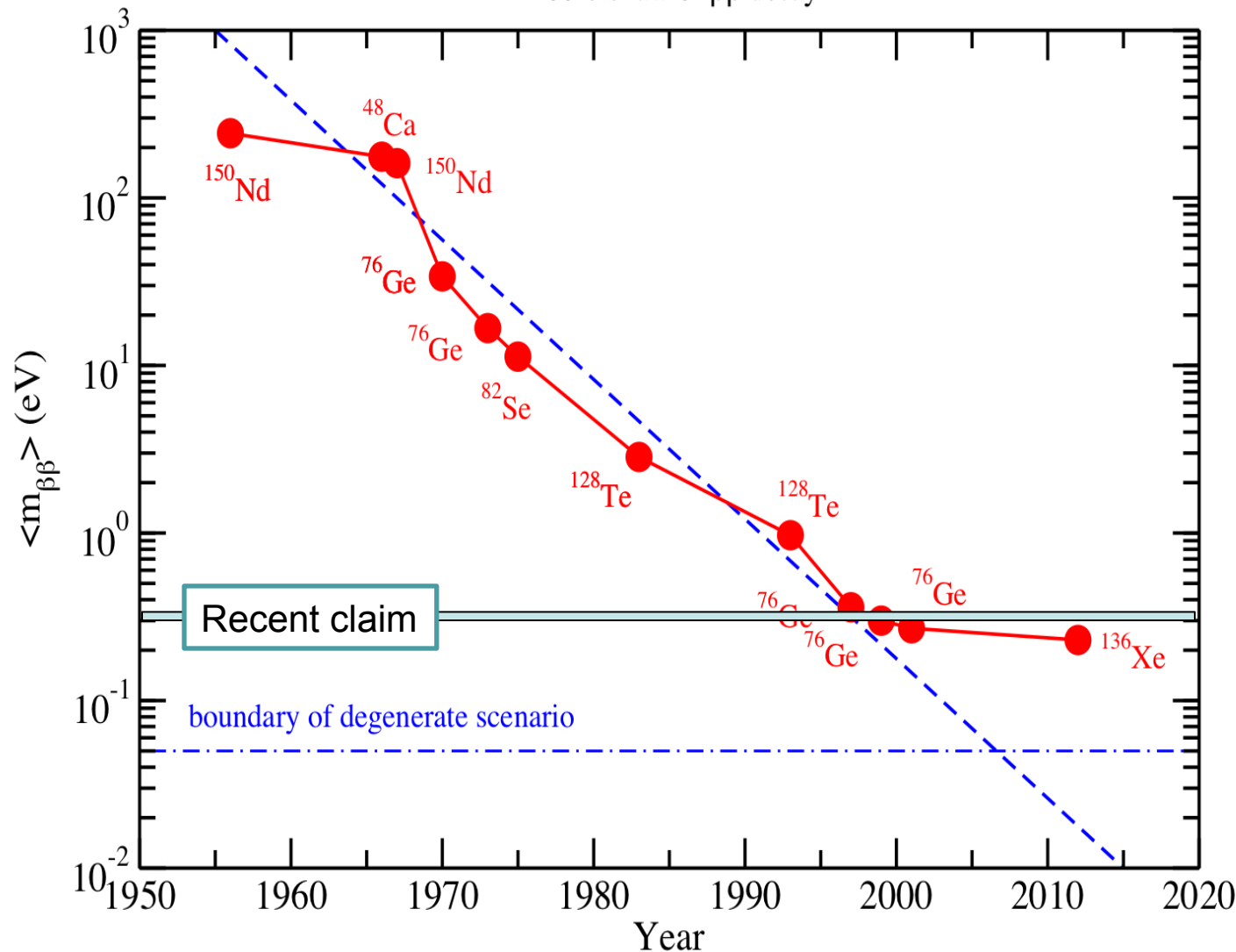
- $\beta\beta(2\nu)$ rate first calculated by Maria Goeppert-Mayer in 1935.
- First observed directly in 1987.
- Why so long? Background
 - $\tau_{1/2}(\text{U, Th}) \sim T_{\text{universe}}$
 - $\tau_{1/2}(\beta\beta(2\nu)) \sim 10^{10} T_{\text{universe}}$
- But next we want to look for a process with:
 - $\tau_{1/2}(\beta\beta(0\nu)) \sim 10^{17} T_{\text{universe}}$

$\beta\beta$ trends (updated Elliott/Vogel plot by Vogel)



History of the $0\nu\beta\beta$ decay

Moore's law of $\beta\beta$ decay



Historically, there are > 100 experimental limits on $T_{1/2}$ of the $0\nu\beta\beta$ decay. Here are the records expressed as limits on $\langle m_{\beta\beta} \rangle$ using one set of nuclear matrix elements (RQRPA of Simkovic et al. 2009.) Note the approximate linear slope vs time on such semilog plot. However, during the last decade the complexity and cost of such experiments increased dramatically. The constant slope is no longer maintained.



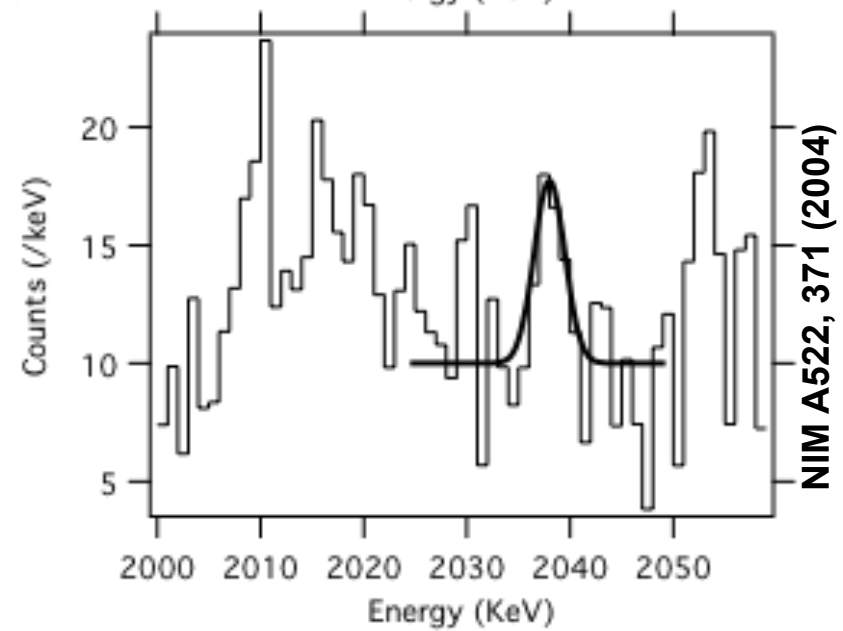
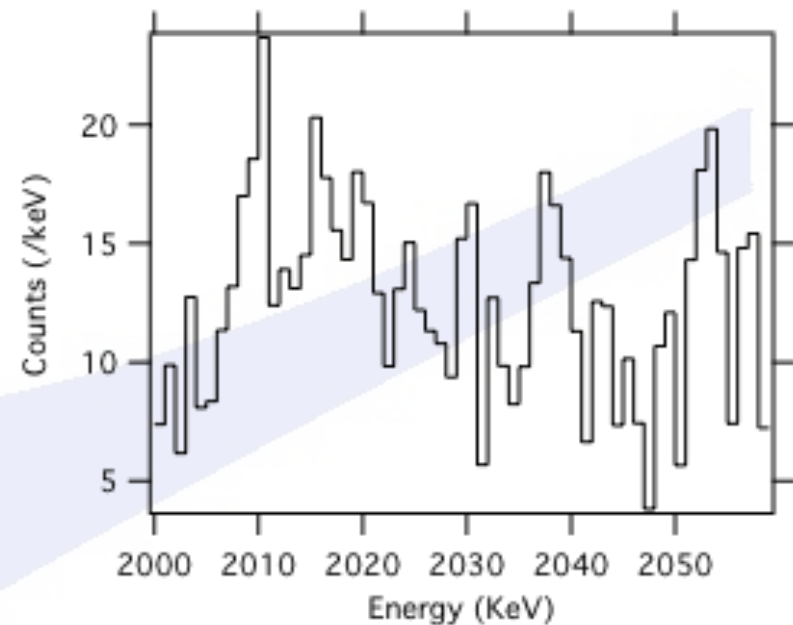
A Claim

has become a litmus test for future efforts

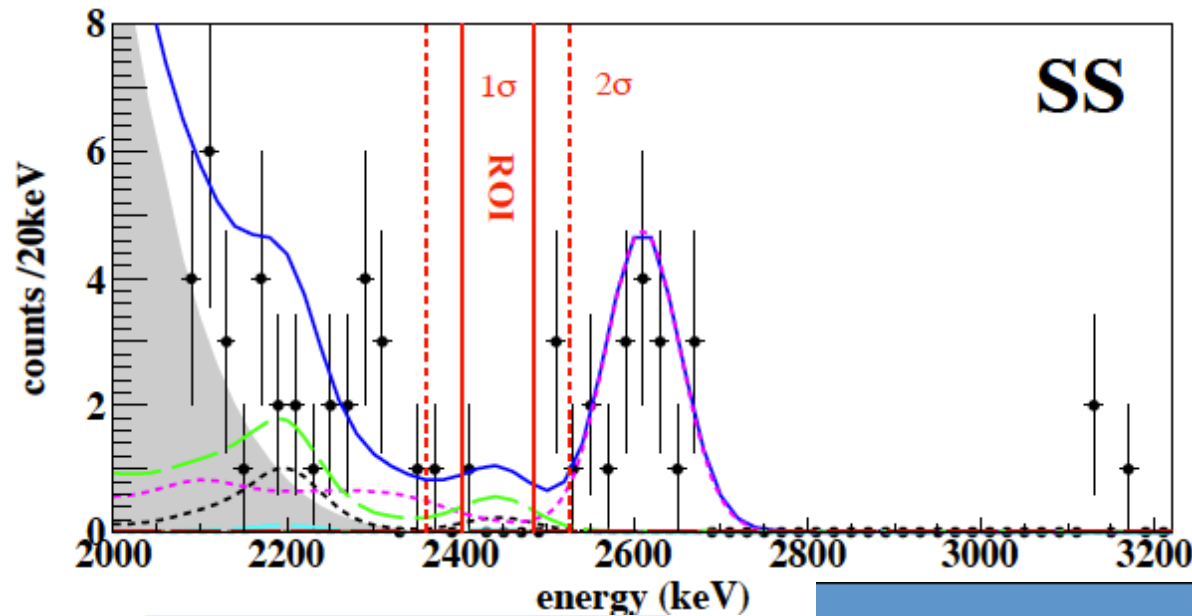
$\beta\beta$ is the search for a very rare peak on a continuum of background.

~70 kg-years of data
13 years

The “feature” at 2039 keV is arguably present.



EXO result



Joint analysis with
KamLAND-Zen gives
 3.4×10^{25} y, 120-250 meV
arXiv:1211.3863

$T_{0\nu} > 1.6 \times 10^{25}$ y
 $m_{\beta\beta} < 140-380$ meV
120.7 days
79.4 kg ^{136}Xe
PRL 109, 032505

	Expected events from fit			
	$\pm 1 \sigma$		$\pm 2 \sigma$	
^{222}Rn in cryostat air-gap	1.9	± 0.2	2.9	± 0.3
^{238}U in LXe Vessel	0.9	± 0.2	1.3	± 0.3
^{232}Th in LXe Vessel	0.9	± 0.1	2.9	± 0.3
^{214}Bi on Cathode	0.2	± 0.01	0.3	± 0.02
All Others	~ 0.2		~ 0.2	
Total	4.1	± 0.3	7.5	± 0.5
Observed	1		5	
Background index b ($\text{kg}^{-1}\text{yr}^{-1}\text{keV}^{-1}$)	$1.5 \cdot 10^{-3} \pm 0.1$		$1.4 \cdot 10^{-3} \pm 0.1$	



Future Data Requirements

Why wasn't the claim sufficient to avoid controversy?

- **Low statistics of claimed signal - hard to repeat measurement**
- **Background model uncertainty**
- **Unidentified lines**
- **Insufficient auxiliary handles**

Result needs confirmation or repudiation



An Ideal Experiment

Maximize Rate/Minimize Background

$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b\Delta E}{Mt_{live}} \right)^{\frac{1}{4}}$$

Large Mass (~ 1 ton)

Large Q value, fast $\beta\beta(0\nu)$

Good source radiopurity

Demonstrated technology

Ease of operation

Natural isotope

Small volume, source = detector

Good energy resolution

Slow $\beta\beta(2\nu)$ rate

Identify daughter in real time

Event reconstruction

Nuclear theory



Signal:Background ~ 1:1

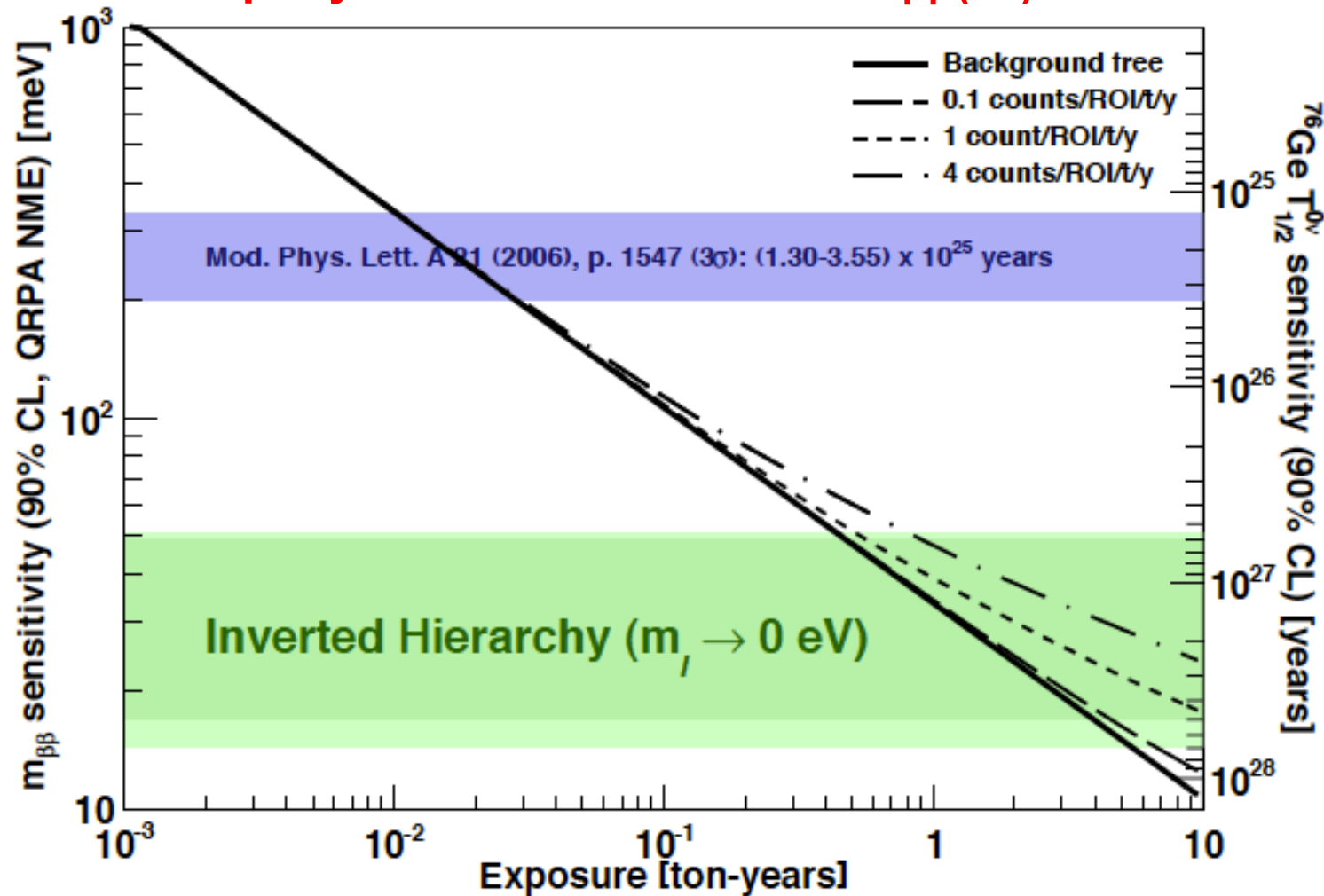
Its all about the background

Half life (years)	~Signal (cnts/ton-year)	~Neutrino mass scale (meV)	
10^{25}	530	400	Degenerate
5×10^{26}	10	100	
5×10^{27}	To reach atmospheric scale need BG on order 1/t-y.	40	Atmospheric
$>10^{29}$		<10	Solar

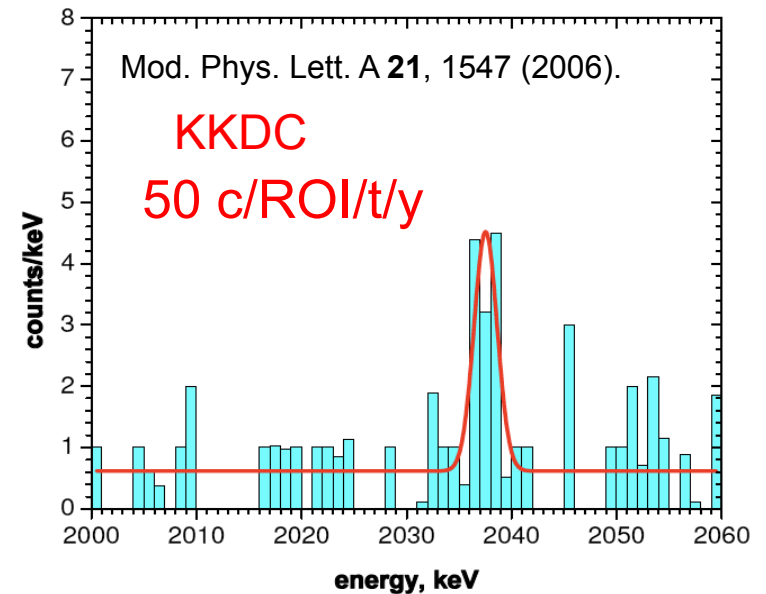
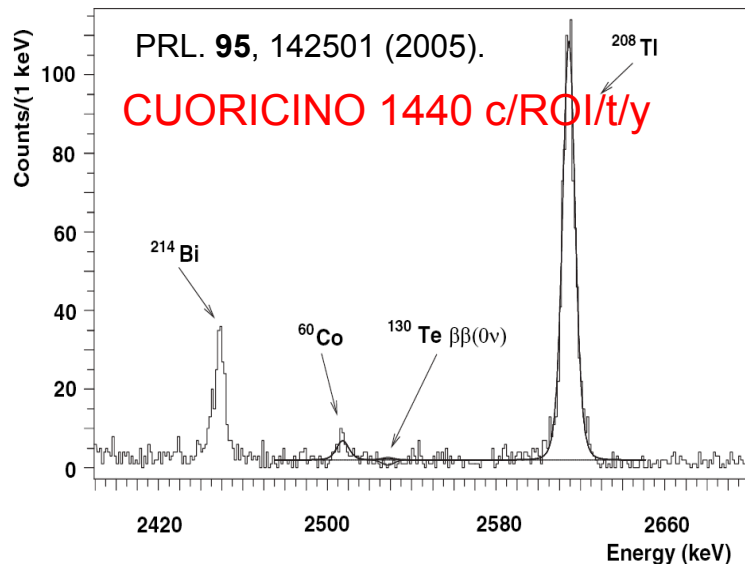
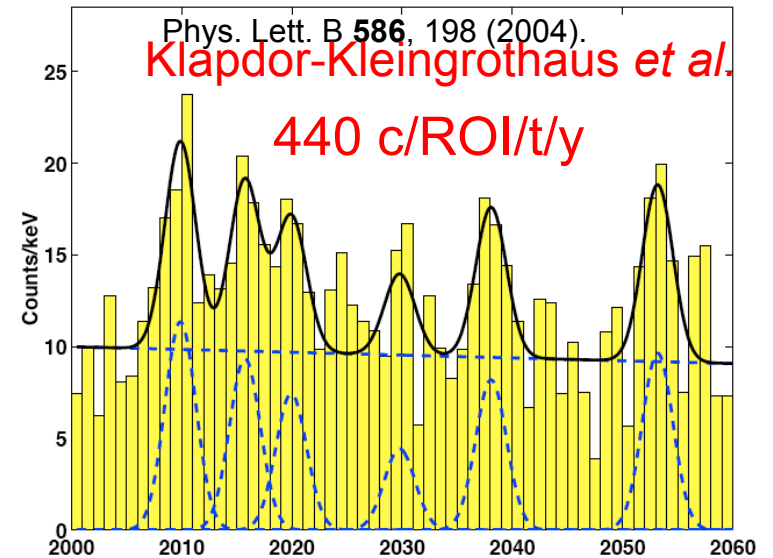
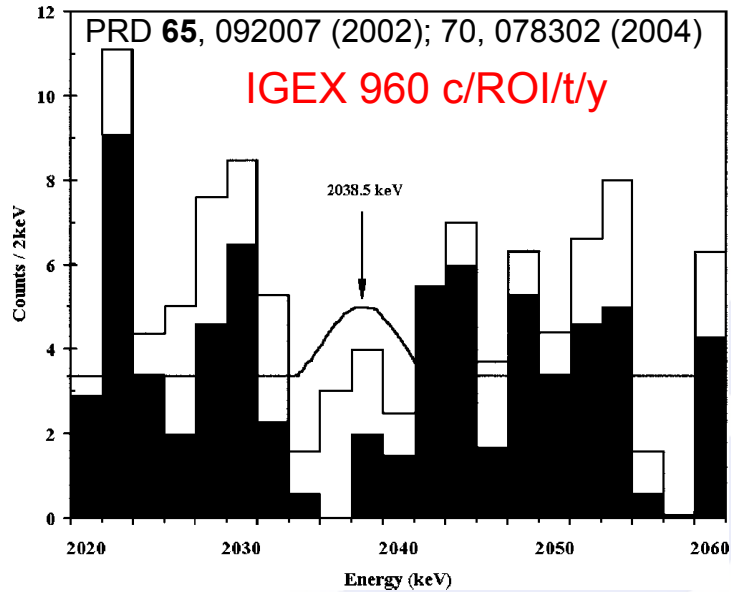
Sensitivity, Background and Exposure



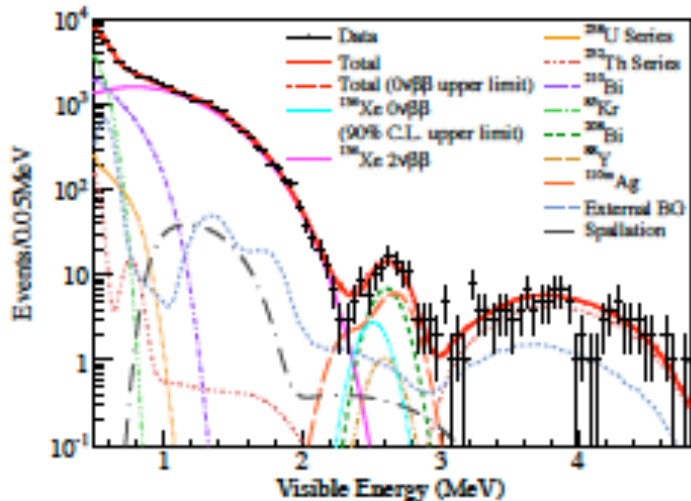
Goal is to achieve ultra-low backgrounds of less than 1 count per ton of material per year in the ROI about the $\beta\beta(0\nu)$ Q-value energy.



Background in Recent Experiments

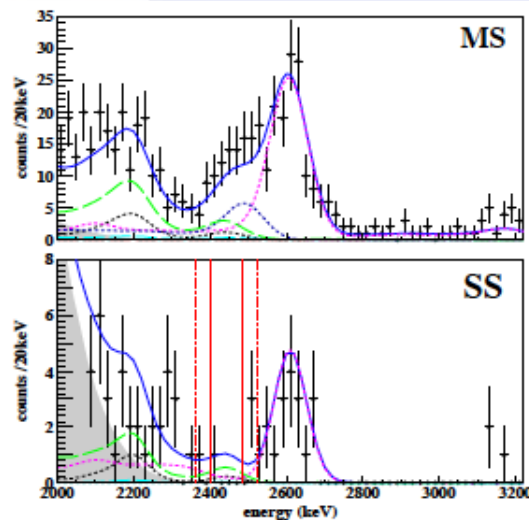


Background in Recent Experiments



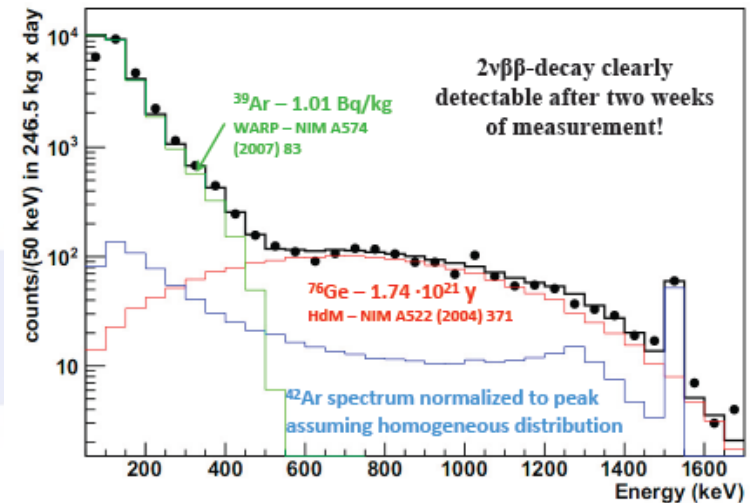
PRC 85, 045504

KamLAND-Zen 2400 c/ROI/t(Xe)/y
EXO-200 129 c/ROI/t/y

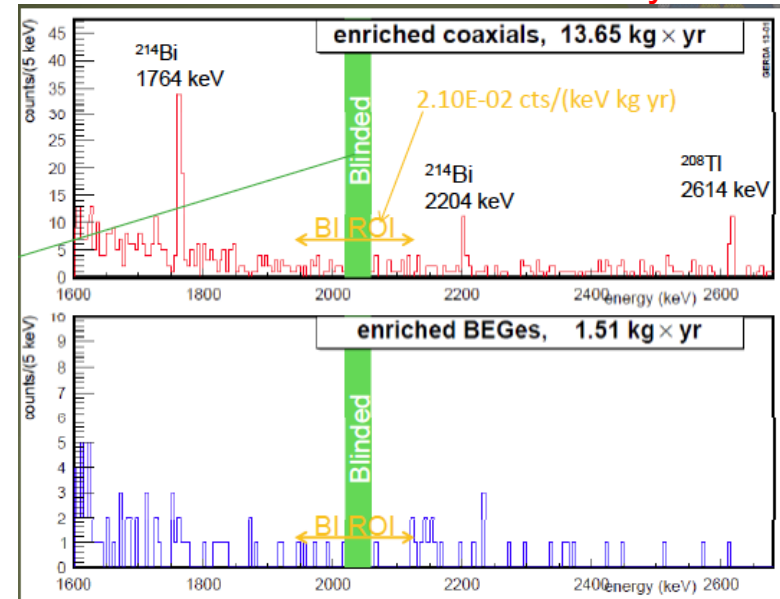


PRL 109, 032505

Low energy spectrum with enriched HPGGe detectors



GERDA – init. enr. 81 c/ROI/t/y



Previous Background Levels



Experiment	Background (cnts/ ROI-t-y)	Width (1 FWHM)
IGEX	960 (400 with PSD)	4 keV ROI
Heid-Moscow	440 (50 with PSD)	4 keV ROI
CUORICINO	1440	8 keV ROI
GERDA	81 (no PSD)	4 keV ROI
EXO-200	130	106 keV ROI (1.8% 1 sig resol.)
KamLAND-Zen	~55(~2400per t(Xe))	Width not explicitly given

Background is per tonne of material – big difference for KamLAND-Zen



Background Considerations

At atmospheric scale, expect a signal rate on the order of 1 count/tonne-year

- $\beta\beta(2\nu)$
- natural occurring radioactive materials
- neutrons
- long-lived cosmogenics

Great Number of Proposed Experiments

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL	^{48}Ca	1 ton	CaF_2 scint. crystals	Development	Solotvina
LUCIFER	^{82}Se	18 kg	ZnSe scintillating bolometers	Development	Gran Sasso
Super					
Sup					
C					
M					
A					
Mo					
C					
C					
F					
Kam					
DCBA	^{229}Th	20 kg	^{229}Th ions and tracking	Development	Kamioka
SNO+[9]	^{150}Nd	43.7 kg	Nd loaded liq. scint.	Construction - 2013	SNOLab
GSO	^{160}Gd	2 ton	$\text{Gd}_2\text{SiO}_5:\text{Ce}$ crys. scint. in liq. scint.	Development	
Quantum Dots[8]	Various		Quantum Dots with isotope in liq. Scint.	Development	

- **Calorimeter**
 - Semi-conductors
 - Bolometers
 - Crystals/nanoparticles immersed in scintillator
- **Tracking**
 - Liquid or gas TPCs
 - Thin source with wire chamber or scintillator

Experiments that will test claim in coming few years.



	Mass	Run Plan
CUORE	~200 kg	2014
EXO-200	~100 kg	2011
GERDA I/II	~34 kg	2011/2013
KamLAND-Zen	~125kg	2012
MAJORANA	~30 kg	2013
NEXT	~100 kg	2014
SNO+	~44 kg	2014
SuperNEMO Dem.	~7 kg	2013

Good guess that we'll reach about 100 meV in the 2013-2015 time frame.

Ton-scale projects might be starting by 2020.

Discovery vs. Measurement

a future decision point



Expt. Size: up to 10 kg

Sensitivity: ~ 1 eV

~ 10 $\beta\beta(2\nu)$ measurements

Expt. Size: 100-200 kg

Several experiments

Program to measure
rate in several isotopes

Expt. Size: 30-200 kg

Sensitivity: ~ 100 meV

Quasi-degenerate

$\sim 8-10$ expts. worldwide

Expt. Size: few T

>3 experiments

Program to measure
rate in several isotopes
Kinematic meas.

Expt. Size: ~ 1 T

~ 3 expts.

Sensitivity: 50 meV

Atmos. scale

Expt. Size: > 10 T

~ 3 expts.

Sens.: 5 meV

Solar scale

1985- Present

2007-2015

2015- 2025

Future



Take-Home Message

- Due to the minimum neutrino mass scale implied by the neutrino oscillation experiments:
 - The next generation $\beta\beta$ experiments have a good possibility of reaching an exciting $\langle m_{\beta\beta} \rangle$ region.
- The MAJORANA DEMONSTRATOR is making strong progress
 - Enriched material order
 - Detector contract in place
 - Lab ready to go
- A large scale experiment will be proposed and R&D is beginning.